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RESISTANCE SPOT WELDING: A REVIEW

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ABSTRACT

Welding is a basic manufacturing process for the manufacture of components or parts with noble mechanical properties. Resistance Spot Welding (RSW) is regularly used as a successful joining method for a variety of jobs in the automotive and manufacturing fields. Precipitation hardening (PH) steels are known to be significant as a structural material among the emerging light alloy steels and are used for fabricating components by conventional metal working processes. The PH group of stainless steel is usually considered to be weldable by the common fusion and resistance technique. A review is carried out on resistance spot welding with different materials, optimization techniques are discussed. Best properties of PH steels are outlined in order to improve the strength properties with conventional welding, analysis on micro-structural variations.

KEYWORDS: Resistance Spot Welding & Precipitation Hardening Steels

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A Review Article

1. INTRODUCTION

The joining of dissimilar materials will have several advantages, including complex mechanical properties, which reduces the cost and weight of the welded parts, which is very necessary in the field of the automotive and aerospace industries. Due to the difficult formation of bonds between two different materials by fusion welding induces metallurgical incompatibility, which includes individualities such as brittle phase formation, high residual stress induced by physical mismatch and segregation of high and low melting phases due to mismatch in the chemical composition[1, 2]. The resulting inter metallic compounds have high hardness and negligible plasticity, resulting in a significant reduction in the mechanical properties of the demanding titanium and stainless steel materials. Resistance spot welding (RSW) is most widely used method for joining materials in the automotive field, which is inexpensive and more efficient. This is the simplest and most widely used form of resistance welding where the surface is joined in a small number of points [3]. Due to the current flow through the work pieces held together by the use of pressurized electrodes, the heat generated by the resistance creates coalescence within a small area. The heat generated depends on the current between the workpieces, the duration and the resistance [4]. It is necessary to maintain the maximum temperature at the interface of the work piece to be welded. In order to achieve this, the resistance of the work piece and the contact resistance between the electrode and the work piece should be kept as low as possible compared with the resistance of the bonding surface. This can be achieved by controlling the contact area, the pressure applied, the electrode material, and its dimensions and working surface quality [5].

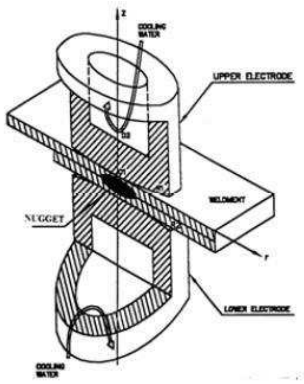

Figure 1: Resistance Spot Welding [3]

The heat gained during the finish of the weld also increases temperature of the electrode and the work piece. Therefore, due to the distribution of heat, micro structural changes may be observed around the weld zone. Heat affected zone (HAZ) must be as small as much as possible in the welds [5, 6]. Alternatively, too much heat in the electrode shortens the life of the cap and reduces the quality of the weld. Therefore, the electrode is cooled by the water circulation of the channel opened inside it. Related research shows that flow rate and water temperature will affect the electrode life and welding quality [7]. In addition, the time and applied pressure are the two important factors for the quality of welding and the life of electrode [8, 9]. The quality of a spot welded joint is defined by dimensions of the heat affected zone and the mechanical properties. Weld strength is calculated by a series of consistent, destructive tests that are subjected to the weld for different types of loads. Some of them are tension shearing, tension, fatigue, impact, and also hardness. The control of the welding factors plays a significant role in the welding quality. The working strength and stiffness of sheet metal parts are strongly influenced by the welding factors and locality of spot welding [10]. So, it is important to choose the welding process parameters to get the best welding strength. In general, the required welding parameters are dependent on experience or manual. However, this will not guarantee that the welding factors selected will generate the best or near optimum welding strength for the particular environment and welding machine.

The heat that was generated by the continuous flowing current will melt the metal and forms the weld joint [11]. The amount of heat released by the current depends on the duration of the current and magnitude. The size and duration of the current must be cautiously controlled and need to match with the type of material used, type of the electrode and thickness. Like other welding processes, the quality of RSW welds is directly influenced by welding input factors. A common problem manufacturer's face is determining and applying process input factors to obtain a good welded joint with the required weld strength. Traditionally, welders set the spot welding process parameters based on their own experience, or use the welding data sheet. Although these technologies provide directions, these methods do not achieve the required quality at the lowest possible cost (power consumption) in producing welded joints with better quality.

Precipitation hardening (PH) steels are known to be significant as a structural material among the emerging light alloy steels. These PH steels can be used for fabricating components by conventional metal working processes. PH steels possess light strength and ductility and corrosion resistance. It is well known that these categories of precipitation hardening stainless steel are available. It is generally believed that stainless steel PH grades can be welded by common fusion and resistance techniques. Considering that heat treatment should follow the best heat treatment conditions for welding, special consideration is required to obtain the best mechanical properties. 17-4 PH stainless steel is one of the most widely used materials in aerospace, petrochemical, chemical, paper making, food processing and general materials

processing industry. 17-4 PH is a Cr-Ni low carbon martensitic containing Cu (copper) and Nb (Niobium) precipitation hardening elements. In the present work the literatures dealing with the mechanisms involved in the resistance spot welding of various types of steels have been summarised. Also, the optimization of the weld joint through various techniques has been evaluated. The parameters include, weld current, applied pressure, heat affected zone etc. It is believed this paper gives in-depth insight about the various aspects of resistance spot welding.

2. NEED OF RESISTANCE SPOT WELDING

Spot welding is a category of resistance welding that is widely used other than rivets, screws, brazing and soldering. The process is widely used to join low carbon steel parts. High strength alloy steels, stainless steels, aluminum, nickel, copper and titanium alloys are commercially available for welding [12]. Two or different metal sheets are joined together by RSW by passing electric current between them. Electrodes are used to conduct the current by pressing the electrodes against the surface of the metal in order to clamp the parts tightly to weld them together.

This welding method with low heat capacity in which heat is produced by resistance of the components welded together and also the interface generate heat for the flow of local current [13]. The cooling frequency of RSW is usually high of about 1000 to 10,000 °C/s) [14]. Therefore, RSW can be used as an appropriate welding method for reducing grain growth, preventing the formation of harmful secondary phases and becoming a promising candidate for welding FSS. Automotive structural components contain thousands of spot welds. Therefore, the performance quality, and failure characteristics of the resistance spot are very important in determining the safety design and durability of the vehicle since these vehicles transmit the load through the structure during the collision [15, 16].

3. LITERATURE ON RESISTANCE SPOT WELDING

Resistance spot welding of AISI 430 stainless steel (ferritic) was performed to observe the phase change. Based on the physical metallurgy technology of ferritic stainless steel welding, the phase transformation during the welding thermal cycle is analyzed in detail. It was found that the fusion zone microstructure and the HAZ were affected by different phenomena such as grain growth, carbide precipitation and martensite formation [17].

The welding time effect of the mechanical properties of automotive sheet in resistance spot welding was studied. In this study, a series of chromided alloyed steel was used and joined by RSW with fixed electrode formats, material types, electrode force, cooling water flow and also by varying welding time and current. All series were tested for tensile peel and tensile shear to determine joint strength. At a welding current of 10 kA, the maximum tensile shear strength values of galvanized chromate steel sheet resistance spot welds were obtained for 12 and 15 cycle weld times. At 12kA welding current for 15 cycles, the indentation depth of the electrode on the work piece is about 15% of the plate thickness. It has been suggested that the above situation is suitable in order to obtain the maximum tensile shear strength. When there is a requirement of surface quality, two methods are effective. One is a 10kA welding current for 10 cycles and the other is a 9kA welding current for 12 cycles. The indentation depth of the electrode into the work piece is 8% of the sheet thickness. These are below the 20% limit to get a good surface. Maximum tensile peel strength values of spot welded chromate steel sheet for 10-time weld time at a welding current of 11 kA. Again, the indentation depth of the electrode into the work piece is 8% of the sheet thickness. These values are below 20% of the steel thickness to achieve surface quality [18].

Resistance spot welding was performed on dual phase steel and the softening of the base metal (BM) and the heat

affected zone (HAZ) was evaluated by a nano indentation hardness test. Along sub-critical HAZs, at different distances from the lower critical temperature line by ferrite and tempered martensite (TM) has been investigated. The SEM observations are consistent with the results of the nano-hardness of the TM phase along the sub-critical HAZ. In contrast, the results of micro hardness show that the tempering distance is shorter relative to Ac1 and therefore reduced extension in the softening region. Improved resolution of the softening assessed by nano-indentation is due to the fact that the size of the indentation can avoid the contribution of the phase boundary and also allows for the evaluation of TM at low temperatures far from Ac1, at which early stage occurs [19].

Ultimate strength behavior of mild steel subjected to combined shear and tension load are investigated. All tests indicate that fracture in the heat affected zone developed shortly after the metal sheet yielded. Moreover, the load carrying capacity of a single resistance spot weld is reduced as the loading angle increases, with approximately a 20% strength reduction from 0° to 90° angles. The tensile strength of a resistance spot weld in mild steel was found to be equal to 80% of the shear strength. The analysis of variance technique was used to investigate the effect of coupon length, coupon width, and nugget diameter on the ultimate strength of the welded coupon. The analysis shows that the nugget diameter and the coupon width are the only two significant factors in the experiment with 99% confidence level and that the nugget diameter contributes more than 70% to the total variation of the test data [20].

The microstructure and failure behavior of different resistance spot welds on low-carbon galvanized and austenitic stainless steels were investigated. It was observed that the strength of spot weld under drawing failure mode is controlled by the strength of the galvanized steel side and the size of the melting zone. The hardness of the fusion zone controlled by the dilution between the two parent metals and the fusion zone size of the galvanized carbon steel side is controlled by failure mode. For spot welding at low welding current, low zone hardness and small zone size lead to an interface mode during shear tensile test. Despite the higher fusion zone hardness due to the formation of martensite and the larger melting zone when spot welding is performed at high welding current, the drawing failure mode occurs during the tensile shear test [21].

The effect of welding current on mechanical properties of resistance spot welded chromided steel was investigated. In the connection of galvanized chromate steel plates, the maximum tensile shear strength is obtained in 15 cycles at a welding current of 10 kA. Since the electrode indentation in the material to a depth of 15% of the sheet thickness and did not exceed 20% of the sheet thickness limit of good surface quality. When the surface quality is higher than the strength, a welding current of 10 kA at 10 cycles of welding time or 9 kA of welding current at 12 cycles of welding time is sufficient. Of these suggested values, the depth of the electrode indentation is 8% of the sheet thickness and does not exceed the limit of 20%. In the bonding of the galvanized chromate steel sheet, the maximum tensile peel strength was obtained when 10 cycles were performed at a welding current of 11 kA. This value is about half the tensile shear strength, indicating the sensitivity of the galvanized chromate sheet welded by RSW to the tensile peel test. This application area recommends 10 cycles of welding current (11kA) because the depth of the electrode indentation in the material is 8% of sheet thickness and does not exceed the allowable 20% limit of surface quality [22].

Resistance spot welding was conducted on titanium sheets with dissimilar welding parameters to evaluate the joint strength. Tensile shear tests were carried out on welded joints to find out the strength of the weld zone. In addition, in order to check the influence of welding parameters on the welded joint, hardness and microstructure examination were performed. The results show that increasing the current time and the electrode force increases the tensile shear strength

and the joint obtained with argon atmosphere has better tensile shear strength. Hardness measurements show that the weld nugget has the highest hardness, as is the heat affected zone (HAZ) and the base metal. Argon used in the welding process is considered to have no effect on the hardness value. Microscopic examination revealed that the weld deformation occurred during the welding process. Twinning occur in grains, the use of high electrode force and high welding cycles during welding increases twinning [23].

The welding test of 17-4PH type precipitation hardened steel is carried out. The possibility of joining centrifugal compressor impeller components as important elements of a turbo machine is considered. High tensile strength and high corrosion resistance are achieved after aging at 893 K/2 h at 1313 K/2 h, or after 893 K/2 h after welding. For centrifugal compressor impeller applications, the use of filter material for 17-4PH steel welding is very effective. 17-4PH steel welded joints have good corrosion resistance. The corrosion occurring in the HAZ mainly has pitting characteristics and the weld with excellent resistance. Lower aging temperature will improve the mechanical properties and hardness, but will reduce the corrosion resistance of welded joints. Aging temperatures above 893K ensure enhanced corrosion resistance. The excellent mechanical properties of the joints provide heat treatment conditions C which is saturated at 1313 K/2 h and aged 893 K/2 h). The joint in heat treatment condition C has the best corrosion resistance to the core wire. Annealing A (893 K/2 h) weld joints to ensure similar mechanical properties, such as heat treatment [24].

4. WHY PRECIPITATION HARDENING (PH) STEELS?

PH steels were primarily developed in the 1940s and it is considered important in a variety of industrial applications that can take advantage of their special properties. Applications that require high strength stainless steel are rapidly growing. Although precipitation hardening stainless steel is high strength, but limited use for powder metallurgy. The addition of these alloys results in the formation of inter metallic deposits during the aging process by adding elements such as niobium and copper. The grade of precipitation hardening shows comparable corrosion resistance to chromium nickel (300 series) grades. Two physical properties and microstructures of precipitation hardened stainless steel powder are proposed. One 17-4 PH, a high chromium, martensitic precipitation hardened stainless steel that has been optimized for PM applications and second, the use of copper in precipitation reactions New low-chromium alloy. The410LCu alloy is considered as a cost-effective alternative for applications which are in need of high strength and medium resistance towards corrosion. Precipitation hardening steel 17-4 PH is widely used in aircraft, petrochemical, food, metal, chemical and papermaking industries due to its high hardness, high corrosion resistance, high strength and ease of heat treatment process. Precipitation hardening sequence is represented in Figure 2.

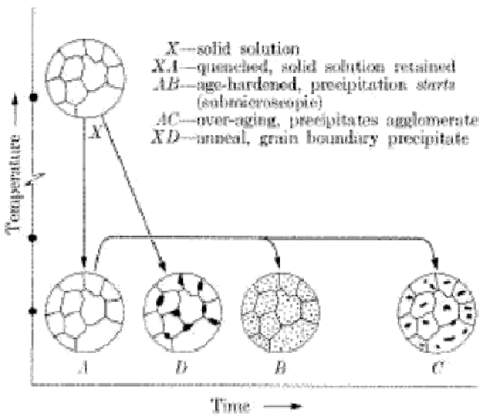

Figure 2: Stages of Precipitation Hardening [25]

Solution treatment is a process in which the alloy is heated relatively to a high temperature, allows any precipitation or alloying elements into the supersaturated solid solution. Distinctive solution treatment temperatures are in the range between 982 °C to 1066 °C (1800 °F to 1950 °F). Quenching where the solution-treated alloy is cooled to produce a supersaturated solid solution. Cooling can be done using water, oil or air. In general, the faster the cooling rate, the finer the grains, the better the mechanical properties. Regardless of the cooling method, the cooling rate must be fast enough to produce a supersaturated solution. Precipitation or age hardening where the quenched alloy is heated to an intermediate temperature for a period of time. At these intermediate temperatures, the saturated solid solution decomposes and the alloying elements form small precipitated clusters. The obtained precipitates impede the movement of dislocations and the metal restricts the deformation and becomes harder. 17-4PH stainless steel parts, traditionally produced by metal injection molding, can be produced by conventional PM presses and sintering operations. The mechanical properties of PM17-4PH can be enhanced by the usage and distribution of finer particle size with elevated sintering temperatures and increased sintering duration. The corrosion resistance property of PM 17-4 PH is similar to the property of 304L when it is treated under similar parameters [26].

Weld ability of precipitation hardened martensitic stainless steels is recognized because these steels are widely used in various industries, particularly in the aerospace field. The literature describes this weld ability as good or very good. People often find positive comments about the low susceptibility to weld cracking. Normally, either pre-heating or post-weld heating is not necessary for obtaining joints up to 100 mm (4 in) thick [27, 28].

Antony [29] investigated the physical metallurgy of precipitation hardened 17-4PH stainless steel. The micrographs (SEM) were proposed to describe the microstructure of the steel as a function of temperature and aging time. In addition to this, different stages of various heat treatments of 17-4PH stainless steel have been proposed after X-ray diffraction data analysis. Later et al.[30] studied the relationship between microstructure and strength, fracture toughness, and low cycle fatigue behavior of 17-4PH stainless steel. They claim that age hardening involves the initial formation of coherent copper-rich clusters that can become non-coherent FCC copper precipitates during future aging. Although 17-4PH stainless steel is currently one of the most widely used precipitation-hardened stainless steels, previous studies of this material focused on general age-hardening reactions or corrosion properties. A lesser work is carried out in 17-4 stainless steel resistance welding.

The small and evenly dispersed inter metallic compounds precipitated in the martensite α-Fe (BCC, a = 0.2866nm) have higher strength and good toughness, Matrix [31-34]. These fine precipitates are solution-heat-treated in the fully austenitic region of the steel and formed during aging at a medium temperature (400-600°C) then quenched into a completely martensitic structure. The type of fine deposit depends on the alloying element. In commercial 17-4 PH stainless steels containing Cu, nano-BCC-Cu or FCC-Cu precipitates during aging [35]. In Fe-20Ni-23Co-0.07Al-0.17Ti PH steel, precipitation hardening is mainly due to the small Ni3Ti intermetallic phase [36]. Many studies have reported that martensitic stainless steels containing nickel and aluminum can be hardened by β-NiAl microparticles (B2, a = 0.2887 nm) after aging at above 400 °C [24][37-40]. Recent 3-D atomic probe (3DAP) studies on PH13-8 stainless steel containing nickel and aluminum show that the stoichiometric composition of the β-NiAl phase is much lower after precipitation for 4 hours at 510 ° C. The size of the precipitate is only a few nanometers (2-8nm), the number density is about 1024m-3. The observed hardening is due to the high density of fine precipitates. Compared with forged 15-5PH and 17-4PH stainless steel it is known that the 13Cr-8Ni-2.5Mo-2Al martensite PH stainless steel of the present invention has

high precipitation hardening properties. This steel is now being considered as a turbine for steam power plant applications [41].

PH13-8 stainless steel is a form of martensitic precipitation hardening steel with high strength hardness, good corrosion resistance and stress corrosion cracking. It also possesses good toughness and ductility over a large cross-section in both in transverse and longitudinal directions and provides enhanced mechanical properties above PH17 and PH15-5 stainless steel in harsh environmental conditions. It has been used in many applications like landing gear components, nuclear reactor and some petrochemical applications which require stress corrosion cracking [42]. The failure phenomenon corresponding to the spot welding due to resistance technique was studied by M Pouranvari et al. [43]. To this end, the specimens made of AISI 304 stainless steel was considered for investigation. SEM has been made use to determine the characteristics during the cross-tension test. They noticed that fusion zone size and hardness parameters are the major factors that control the failure mode of AISI 304 resistance spot welds. For both cross tension and tensile shear tests, it was noticed that the peak load of the welds increased with respect to the fusion zone size. In addition, various parameters such as sheet thickness, fusion zone size, and hardness characteristics also have a predominant influence.

The model to describe the resistance spot welding method was developed by Tsai et al. [44]. Further, they simulated the entire process with the aid of finite element procedures. In addition, they also evaluated the formation of weld nugget during resistance spot welding of ASS 347 grade austenitic stainless steel. For this evaluation, they considered both equal and unequal thicknesses. They extended their evaluation to thoroughly study the effects of adding ASS 347 austenitic chrome steel to ASS 1045 carbon steel. It has to be mentioned that the FE model considered for the analysis has the potential to take into account the transient thermal response of resistance spot welding.

The evaluation of the welding time on the tensile, peel strength was carefully examined by Donders et al. [45]. Also, the made a study to investigate the tensile shear strength of welding joints when subjected to electrical resistance spot welding. In this regard, chromate micro-alloyed steel sheets were taken into consideration. A fixed electrode pressure was applied to obtain the weld. As a next step, tensile shear and tensile, peel tests were performed with the joints and evaluation was made on the effect of welding time. Finally, the optimum welding times were researched.

The influence of spot weld diameter and the pitch of spot weld on the structural characteristics were investigated by Rusinski et al. [46]. Also, the effect of geometrical nonlinearities was carefully assessed by using FE methods. They found that the strength of spot welded structures is predominantly affected by the diameter of the spot. They extended their study to assess the vibration of plates embedded with spot welded stiffeners.

Palmonellaet al. [47] studied the effect of spot welded on the natural frequency characteristics of the structures. They also proposed the techniques to optimize the design and improve the structural dynamics of the spot welded structures. It consistsof thousands of spot welds which majorly influences on the structural dynamics of the whole body. Murat et al. [48] have studied on resistance spot weld ability of galvanized interstitial free metal sheets with austenitic stainless steel sheets.

The various mechanical properties of spot welded dissimilar joints were assessed by Alenius et al. [49]. The different parameters involved in spot welding were examined. It is found from their study that spot weld capability significantly depends on the numerous parameters. Also, this gives a brief insight on the spot weld capability of numerous metallic joints between stainless steels and non stainless steels.

Alizadeh and Marashi[50] addressed the failure analysis of austenitic and duplex stainless steel with dissimilar resistance spot welding. With the help of scanning electron microscope, the observed that the heat affected zone underwent solid state phase transformations due to the presence of TiC particles in the base metal microstructure of the duplex stainless steel. Also, they noticed that in the fusion zone transition from columnar to equiaxed grain structure existed. This can be attributed to the heterogeneous nucleation. Their study also dealt with grain boundary liquation present in the heat affected zone. From their study, it is revealed that in a manner similar to pullout failure, partial thickness failure occurs. And the parent metals act as a key deciding factor with respect to crack initiation site.

Verma et al. [51] employed Taguchi methods and made a characteristic study to evaluate the properties of spot welding of dissimilar metals. Efforts are made to assess the weld quality subjected to tensile-shear testing. Also, the variation of the weld metal size with respect to various parameters has been carefully examined. From their evaluation, it can be summarized that the tensile shear strength of the welds is predominantly influenced by welding current. In addition, the variation electric resistivity leads to the development of asymmetric fusion zone. Further, the significant influence of weld time and pressure are also witnessed.

Due to the interaction of the mechanical, electric and thermal phenomenon, the resistance welding is found to be very complex. Also, the entire process can be treated as non-linear. This makes the computational analysis tedious. In this regard, Nied[52] simulated this complex coupled process using the axi-symmetric finite element model. The researcher made use of iso-parametric solid element to represent the work piece and the electrode. The verification of the FE model was done on AISI 321 grade austenitic stainless steel.

In the spot resistance welding of AISI304 grade austenitic stainless steels, the tensile shear load bearing capacity (TSLBC) was reliably predicted by Martin et al. [53]. With the lapse of time it was found that the proposed model can be effectively used to analyze squeeze and weld cycles. It helped to evaluate the different responses which included electric, thermal and mechanical fields. Further, the authors were capable to obtain the temperature variations, thermal expansion and related stresses with the help of this model. In addition, the weld nugget was also predicted accurately using this model.

The transient thermal response of the resistance welding process was simulated through 2D axi-symmetric FEM model by Thakur et al. [54]. To this end, PLANE223 element was made use of, which could effectively simulate the thermal behaviour of resistance spot weld. Further, this study also helped to predict the phenomenon behind the welding process which yields optimization of different welding parameters. Y Zhang et al. [55] considered 1Cr18Ni9Ti stainless steel material for their evaluation and examined the cooling rates appearing in the various regions of spot welded nugget. For this purpose, they used the rapid solidification theory and Fourier-Wunderlin secondary dendrite arm spacing (SDAS) model. The results revealed that the cooling rate decreased drastically from the nugget edge to centre in an order of 10^5 to 10^4 Kelvin/sec.

Mehdi Mansouri Hasan Abadi et al. [56] in their study were successful to establish a relationship between structural arrangement and mechanical properties of resistance spot welds which are dissimilar. In their evaluation they considered AISI 304 austenitic stainless steel and AISI 1008 low carbon steel. The effect of spot welds growth on the dissimilar joint growth was studied with an example, considering AISI 304 stainless steel and carbon for evaluation Nachimani Charde [57]. The specimens were of different thickness. The investigated in detail the effect of welding parameter changes in the characteristic behavior of wild growth. They extended their evaluation Nachimani Charde [57]

for 304 austenitic stainless steel and carbon steel comprised of different thickness. They concluded that due to the heat treatment process, the hardness increments of welded side are noticed very clearly.

Kolarık et al. [58] witnessed a broader heat affected zone of low carbon steel sheet in comparison with that of austenitic stainless steel. Also, the ferrite grains were refined at low temperature heat affected zone of carbon steel. In addition, the hardness in the fusion zone was a bit higher in contrast to other zones of the weld.

A. K. Biradar et al. [59] evaluated the behaviour of resistance spot welding of dissimilar metal between mild steel and AISI 304 austenitic stainless steel, having medium range thickness. The influence of different welding parameters such as welding time, welding current and welding force on the weld quality was evaluated. A polynomial equation of first order to correlate weld strength with weld time, weld current and weld force was developed. For the resistance spot welding of AISI 304 stainless steel, Shamsul et al. [60] evaluated the correlation between nugget diameter and welding current. The emphasize has also been given for analyzing the distribution of Hardness along the welding zone. From the results it can be interpreted that welding current is directly proportional to the nugget diameter, whereas the hardness distribution appears to be unaffected with respect to the welding current. A similar behavior is noticed for nugget size.

The influence of prominent parameters such weld load, arc intensity, duration of the welding on the structural characteristics of the weld joint related to austenitic stainless steel has been dealt in detail by Bouyousfi et al. [61]. Their evaluation reveals that the load applied acts as a significant controlling factor in comparison to the weld duration and current intensity. M. Pouranvari et al. [62], in an another study on RSW of stainless steel, investigated the effect of welding current on different parameters like energy absorption capability of austenitic stainless steel AISI304 with RSW during the quasi-static tensile shear test. The achieved results showed a straight relationship with fusion zone size and failure energy.M. Pouranvari [63] studied the failure mode of AISI304 grade stainless steel resistance spot welds. The results of quasi-static tensile-shear test are obtained for examination. The results from the experimentation suggested that the conventional weld size of $4\sqrt{t}$ is insufficient to resist the pullout failure mode for AISI304 stainless steel RSWs during the tensile - shear test. Hence, it is not recommended. Further, they developed an analytical method to estimate the minimum fusion zone required to avoid the pullout failure. This model took into consideration, the effect of failure location and failure mechanism. From their evaluation, it can be concluded that along with the thickness of the sheet which is being welded, the ratio of fusion zone hardness to failure location hardness plays a vital role in deciding the failure mode of spot welds while carrying out the tensile shear test. The spot welding phenomenon between the dissimilar materials like Stainless Steel and Low Carbon Steel was investigated by

Agustinus Eko Budi Nusantara et al. [64]. In order to estimate the impact of the welding current accounting to the different material properties of the weld joint many experiments have been carried out. It is found from their study that the nugget size and tensile-shear load bearing capacity of the joint drastically increases when the welding current increases.

Along with tensile strength of the weld joint, it is very much necessary to evaluate the fatigue strength of the resistance spot weld joints formed at the interface of various steel sheets. In this regard Vural et al. [65] considered this study and carried out experiments on the galvanized steel sheets and austenitic stainless steel. They found from their evaluation that with the variations in the loading conditions, the fatigue strength of the joints has a predominant effect. Triyono et al.[66] made a comparative study on the fatigue strength of resistance spot-welded unequal and equal sheet thickness austenitic stainless steel grade AISI 304. Due to significant thickness difference, the asymmetric weld nugget, high micro hardness on the edge of nugget and tearing fatigue fracture mode were reported.

5. OPTIMIZATION TECHNIQUES

Resistance spot welding because of its simple principle, cost-effective and other characteristics, is widely used in automobile body and other steel processing sheet connection. However, even in a process where resistance spot welding is easy to apply, the factors that determine the quality of welding also greatly affect each other, making it difficult to obtain satisfactory welding quality. Setting the conditions required to obtain the required weld quality using trial and error is an inefficient task. Therefore, it is necessary to determine the best conditions that can produce the desired weld quality by using a welding process model that expresses the quality of the weld with the fewest number of experiments [67]. The optimization of the spot welding has been carried out by Chinmoy Mondal et al.[68] for the case of precipitation hardening stainless steel. The method followed by them to accomplish the requirement is the analytic hierarchy process. From their experimentation, they obtained a superior quality of weld nuggets when the weld current of 2.5 kA was used. Further, they varied the parameters such as welding time of 6 to 7 cycles and also with another current value of 6 to 7 KA with a welding time of 5 cycles keeping the load as constant at 4 KN. It can be clearly noticed from their study that the welding parameters such as current, time and load plays an important role in obtaining superior weld quality. The optimization studies were extended by T Wray [69]. The researcher considered different parameters such as time, current and pressure related to the resistance spot welding. In this regard, a duplex stainless steel was considered for evaluation. The optimization experiments were performed to achieve the best micro- and macrostructures. It included the variation of the welding current between 4.7 to 5 kA with 15 cycles for 2101 and SAF 2304, 20 cycles for 2205 and 25 cycles for SAF 2507. They maintained the electrode force was 3.25 kN with the nugget diameter was 4.5 to 4.9 mm.

5.1 Taguchi Method

Optimization of the parameters is an important step for Taguchi's approach to achieve high class in quality at no additional cost. This is because, the optimization of the process factors can improve the quality, and the optimum process factors or parameters achieved from the Taguchi method are not sensitive to changes in environmental circumstances and other factors. Usually, the classic design of process parameters is difficult and it is not easy for usage [70].

One of the advantages of Taguchi's method is that it emphasizes the average performance characteristic value near to the objective value, not the value within a certain specification, thereby improving product quality. In addition, Taguchi's experimental design methodology is direct and easy to apply in many engineering conditions which make it one of the powerful and easy tools. This method can be used rapidly to narrow the scope or identification of research projects. Problems in the manufacturing process already exist [71]. The main drawback of the Taguchi method is that the results achieved are only comparative and do not accurately specify that what parameters have the greatest impact on the performance eigen values. Moreover, since orthogonal arrays cannot test all combinations of variables, this method cannot be used for all relations between all variables. The Taguchi method has been criticized in the literature as an inexplicable interaction parameter. Another drawback is that the Taguchi method is not online and therefore not suitable for processes which are changing dynamically like mock studies. In addition, even though with poor quality of Taguchi's approach to design quality, they are efficiently applied in the primary phases of process improvement [72].

When the process parameters are increasing in numbers, a number of experiments must be conducted. To resolve this task, Taguchi's method uses a distinct design of an orthogonal array to study the complete process parameter, requiring merely a small amount of experimentation. Using orthogonal arrays to design experiments can help designers to investigate the impact of multiple manageable aspects on average and variation in quality characteristics in a fast and cost-

effective manner, while analyzing experimental data using signal-to-noise ratios can help the product or manufacturer Designers can easily find the best combination of parameters. Then define the loss function to calculate the abnormality between the experimental and expected value.

Taguchi will recommend using the loss function to measure the abnormality of the quality characteristic from the expected value. The overall value of the loss function is further converted to a signal to noise ratio (S/N). In this(S/N) ratio analysis, there are usually three types of quality features, namely the lower the better and the better the better. The S/N ratio of each stage process parameters is calculated based on S/N analysis. Regardless of the type of quality characteristic, a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimum level of process limits is the maximum S/N ratio. In addition, a statistical analysis of variance (ANOVA) was conducted to observe which process factors were statistically important. The best arrangement of process factors can then be projected [73].

5.2 Response Surface Methodology

In RSM, many parameters like environmental conditions and control factors define weld quality such as weld current, weld time, weld force, tip wear, surface condition and work piece thickness i.e., AWS 2000. This study uses the welding time, welding force, welding current, to analyze the welding quality, because these are the factors that affect the welding quality. The Response surface methodology is widely used to achieve optimal process conditions. This method was used to examine the influence of the above features on the shear strength, the effect of the electrodes pressing the sheet surface and the discharge of the weld metal between the sheets. According to the data obtained through this experiment to develop welding process model to express the weld quality, and use the model to determine the best welding conditions in the region of interest. The Response surface methodology includes experimental design of neighboring models between input variables and output variables, statistical modeling that shows the relationship between input variables and output variables, and optimization of output variables. The welding time, welding force and welding current are termed as input variables, indentation and weld shear strength are termed as two output variables. In addition, since the three input and output variables are intertwined in a complex manner, a second order regression model is used as the response surface model as represented in the relation (1).

$$y_k = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ii} x_i^2 + \sum_{j=2}^{3} \sum_{i=1}^{j-1} \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

Where, xi is the coding unit for the input variables (welding time, welding force and welding current) and yk is the output variable (indentation and shear strength) that represents the quality of the RSM. In addition, β is the regression coefficient acquired from the experimental result and is found from the least square method. The data obtained by an experiment with reference to the welding quality need to obtain the second-order model equation (1). Central Composite Design (CCD) was used as a highly efficient experimental design method in this study, because of the budgetary issues that may stand up when conducting experiments through tiresome trial and error processes [67].

6. CONCLUSIONS

Resistance spot welding can be carried out on different types of steels based on the requirement in different applications. In resistance spot welding, a clear understanding of the different parameters such as the surface condition, weld size, weld current, applied pressure and distribution of heat affected zone is very much necessary. Many literatures

have been carried out and encapsulated the significant influence of these parameters on the weld joint. It can be concluded that the interface resistance of the weld joints has a negligible effect in resistance welding. Further, the tensile shear strength of the welds is predominantly influenced by welding current. The hardness in the fusion zone was a bit higher in contrast to other zones of the weld. Meanwhile, it can be interpreted that welding current is directly proportional to the nugget diameter, whereas the hardness distribution appears to be unaffected with respect to the welding current. Literature also concludes that 17-PH steels give better mechanical and corrosion properties. Weld ability of precipitation hardened martensitic stainless steels got universal recognition in the field of automotive and aerospace industries.

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